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The design and environmental evaluation of earth-to-air heat exchangers (EAHE). A literature review

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ABSTRACT

There is a rising interest in heating and cooling systems based on renewable energy sources. Air heating or cooling with earth-to-air heat exchangers (EAHE) is one approach for reducing ventilation heat losses and improving thermal comfort in buildings. A literature research was performed in order to analyze the design, characteristics of earth-to-air heat exchangers and whether they could be coupled with HVAC system coupling. A range of projects was compared in order to collect and summarize design suggestions.

Contents

1. Introduction

There is a rising interest in heating and cooling systems based on renewable energy sources. The ground source heat pump (GSHP) systems are a suitable alternative to conventional systems to reduce the primary energy consumption required for heating and cooling of buildings [1]. In these systems, the heat pump is generally used for both the space heating and cooling; as a matter of fact, the ground acts as a heat source in the winter and a heat sink in the summer. As well known, the energy efficiency of the heat pump directly depends on the heat source/sink temperature, i.e. on the ground temperature. In closed loop systems, the heat

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Nomenclature

a	absorptance of surface [–]
c_a	specific thermal capacity of air [J/(kg K)]
c_p	specific heat of the air [J/(kg K)]
g_v	condensating/evaporating amount of water vapour [kg/(m^2 s)]
h	convective heat transfer coefficient [W/(m^2 K)]
I	total incident solar radiation on the surface [W/m^2]
l	latent heat condensation [J/kg]
$\dot{m}$	air mass flow rate through the tube [kg/s]
m_a	air mass flow rate [kg/s]
$r_{p,i}$	internal radius of the pipe [m]
$r_{p,o}$	external radius of the pipe [m]
t	time [s]
T	temperature [K]
V_a	air volume flow rate [m^3/s]
z	ground depth [m]

Greek symbols

α	soil thermal diffusivity [m^2/h]
β_p	moisture transfer coefficient [m/s]
ε	emittance of surface [–]
λ	thermal conductivity of the soil [W/(m K)]
ρc_p	volume heat capacity of the soil [J/(m^3 K)]
ρ_v	water vapour concentration of the air in EAHE [kg$_v$/m^3]
$\rho_{v,\text{sat}}$	saturated vapour concentration [kg$_v$/m^3]
σ	Stefan–Boltzmann constant: 5.67×10^{-8} W/(m^2 K^4)

Subscripts

d	delivery
ext	external
g	ground
m	mean
s	suction
w	surface of the pipe

pump is coupled with the ground by means of heat exchangers, that can be vertically or horizontally oriented. Copious was the theoretical and experimental work on GSHP systems [2–14].

In this paper a particular earth coupled heat exchanger is analyzed, which is the earth-to-air heat exchanger (EAHE). Due to the high thermal inertia of soil, temperature fluctuates much less below the ground than at surface level. At a sufficient depth, soil temperature is lower than the outdoor temperature in summer and higher in winter. When ambient air is drawn through buried pipes, the air is cooled in summer and heated in winter before it is used for ventilation. An earth-to-air heat exchanger (EAHE) system consists of a network of buried pipes through which air is transported by a fan. In summer the air supplied to a building is cooled and dehumidified because the soil temperature around the heat exchanger is lower than the ambient temperature. During winter, when the ambient temperature is lower than the soil temperature, the process is reversed and the air is pre-heated. The main advantages of the system are discussed in this paper.

2. Methods

Literature was searched by using the following key terms: earth-to-air heat exchanger (EAHE, EAHX, ETAHE, ATEHE), buried-pipe system, preconditioning of air, and ground-coupled heat exchanger. Selected proceedings and conference papers were also searched, as was a number of electronic databases, including Web of Science, PubMed, Sciencedirect and Google Scholar.

This paper analyzes the following:

- Evaluation of EAHE design, characteristics, and coupling with HVAC systems.
- EAHE performance: existing models and related algorithms used to evaluate heat transfer with the surrounding soil and thermal behavior of pipes. Simulation programs are also described.
- Case studies: building types, location and different approaches to evaluating EAHE systems.

This literature search enabled us to outline suggestions and best practices for designing future systems, including EAHE.

3. Evaluation of EAHE design, characteristics and coupling with HVAC systems

An EAHE system typically consists of an inlet shaft with filters and a network of pipes buried in the ground through which air is transported by a fan (Fig. 1).

The network of buried pipes can be installed in open spaces (Fig. 2a and b) or beneath buildings (below the foundation slab) as a grid, serpentine or ring layout. The ring layout is used around paved areas (see Fig. 2(c)) [15].

Open-loop and closed-loop are the two main types of EAHE. Each one takes air from a different point, the former from outdoors, the latter from indoors [16].

EAHE components are described in Table 1.

3.1. Working principle of an earth-to-air heat exchanger

The principle of using soil thermal inertia dates back to the ancient Greeks and Persians [20]. In Medieval Italy, special caves called 'covoli' were used to precool or preheat air before it entered a building. The energy performance of EAHE depends on the heat transfer between the soil and air inside a pipe. Fig. 4 illustrates the

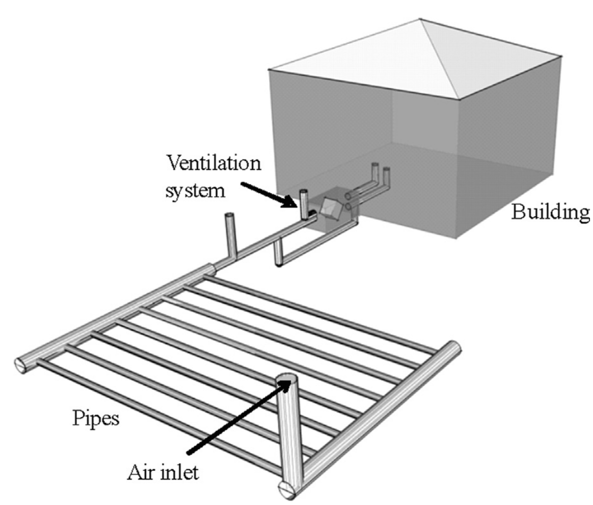

Fig. 1. Example of an EAHE.

Fig. 2. Different pipe layouts below ground level.

Table 1
Component description.

	Material	Features	Function
Air inlet			
Air intake tower	Stainless steel	Dimension: ~2 m High efficiency filter	Introduce and filter outdoor air
Pipe			
Seamless pipes	Steel [17–19] Aluminum [20,21] Plastic: PE, PVC, PP[a] Copper[b]	Resistance coefficients, wall roughness, diameter, length, and burying depth. Pipes should be anticorrosive, structurally stable and accessible for inspection and cleaning	Transport air and exchange heat with soil
Stony pipes	Concrete Brick		
Fan			
Air intake fan		Diameter, height and filter type	Take air from outdoors
Exhaust fan			Remove exhaust air
Condensation management		Two types: integrated and standalone	Drain condensation and expel water

[a] The most widely used today [22].
[b] Early applications [17].

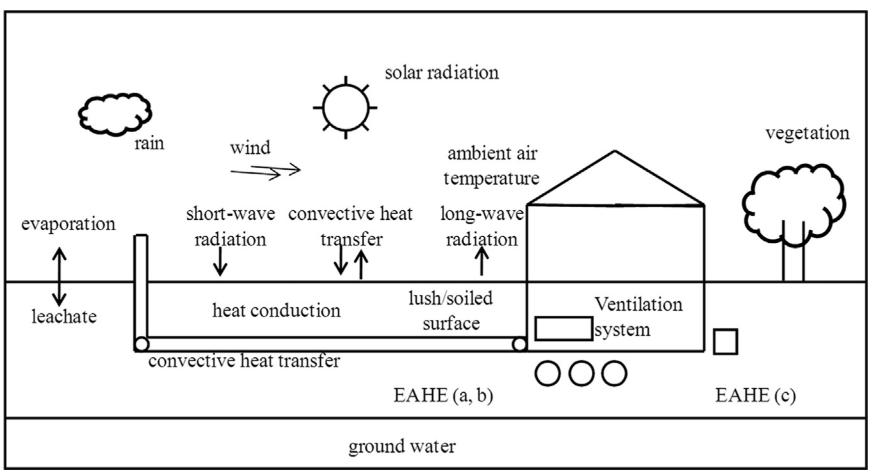

Fig. 3. Environmental factors and heat-transfer mechanisms that influence soil temperature [23].

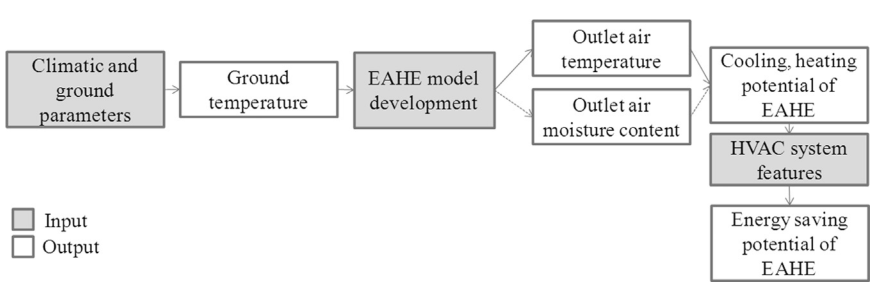

Fig. 4. Steps in evaluating EAHE performance.

main conditions that influence heat and mass transfer within an EAHE. See Fig. 2 for EAHE types (a, b and c).

Heat is transferred to or from the surrounding soil by conduction through the pipe thickness and by convection with the pipe's internal surface (Fig. 3). Conduction heat transfer is transient and fully three-dimensional in the soil [19]. Condensation and evaporation should also be taken into account. A general diagram can be drawn up to evaluate EAHE performance (see Fig. 4).

The first step is to calculate ground temperature on the basis of climatic and ground parameters. The second is to calculate outlet air parameters, which are influenced by EAHE characteristics. EAHE models are described in the next part. Once outlet air

parameters have been calculated, cooling (Q_c) and heating potential (Q_h) integrated during summer/winter can be calculated with the follow equations:

$$Q_h = \dot{m} \times c_p \times (T_d - T_s)\Delta t \quad [\mathrm{J}] \tag{1}$$

$$Q_c = \dot{m} \times c_p \times (T_s - T_d)\Delta t \quad [\mathrm{J}] \tag{2}$$

where Δt is the calculation time step [s].

3.2. Calculating soil temperature

When analyzing natural heat flow in a shallow soil region, the ground may be considered a semi-infinite solid and heat conduction is calculated with Fourier's Law. The daily mean ground surface temperature follows a harmonic variation, and its yearly amplitude is more or less equal to that of the air. Kusuda and Achenbach [24] have mathematically modeled Eq. (3), which describes/calculates the annual sub-surface soil temperature based on heat conduction theory applied to a semi-infinite homogenous solid [25].

$$T_g(z,t) = T_m - A_{\mathrm{surf}} \times \exp^{[-z(\pi/8760\alpha)^{0.5}]} \times \cos\left[\frac{2\pi}{8760} \times \left(t - t_0 - \frac{z}{2}\left(\frac{8760}{\pi \times \alpha}\right)^{0.5}\right)\right] \tag{3}$$

where t is the time elapsed from the beginning of the calendar year in hours; T_m is the annual mean soil temperature [°C]; A_{surf} is the amplitude of surface temperature variation [°C]; and t_0 is the phase constant of the lowest average/mean soil surface temperature in hours since the beginning of the year.

The annual mean soil temperature is generally estimated by considering the annual average/mean air temperature. This assumption is valid when there is no anomalous gradient temperature or significant groundwater flow.

The results of Eq. (3) are shown in Fig. 5, which uses the following parameters: soil volume heat capacity equal to 2.07 MJ/(m^3 K), soil thermal conductivity λ equal to 1.8 W/(m K), T_m equal to 13 °C, A_s equal to 11 °C, and t_0 equal to 31 days.

A detailed model has to take into account the interaction between the ground and the ambient environment. The ground surface interacts with the aboveground environment; the rate of heat entry into the ground surface is a combination of convection heat transfer with external air, incident solar radiation and radiant heat exchange with the sky. As a consequence, the heat balance for the ground surface is expressed as follows:

$$Q_{\text{conduction into the ground}} = h_{\mathrm{ext}} \times (T_{\mathrm{ext}} - T_g) + a \times I - \varepsilon \times \sigma \times (T_g^4 - T_{\mathrm{sky}}^4) \tag{4}$$

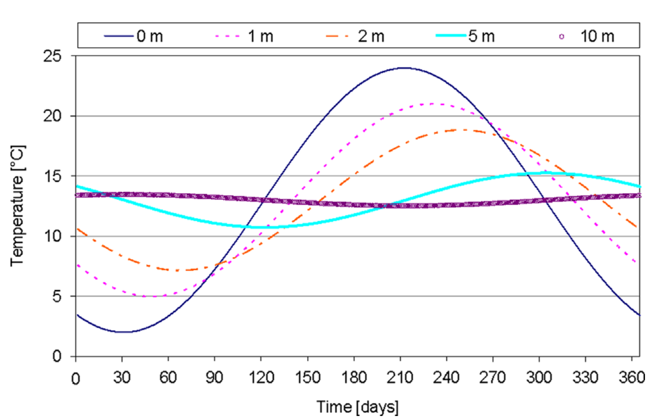

Fig. 5. Example of ground temperature oscillation calculated with the Kusuda and Achenback model [24].

Short- and long-wave radiant heat exchange at a depth of between 1 and 2 m has a major effect on the top layer of the soil. For this purpose a detailed numerical model based on the finite difference method was developed. In this model, Eq. (4) expresses the heat balance of the ground surface and under the ground the heat transfer takes place only by heat conduction. By means of this simulation tool, the effect of the aboveground environment on the soil temperature for two Italian cities (Milan in the North and Palermo in the South) was analyzed. This study considers the test reference years [26] of the cities analyzed. The specific convection thermal resistance was set to 0.067 m^2 K/W; the absorptivity and emittance of the ground surface was assumed to be equal to 0.8 and 0.9, respectively. The sky temperature Tsky is determined with Swinbank's correlation [27]. Fig. 6 illustrates the temperatures calculated. Fig. 6a–c shows the results when only external air temperature is applied as a boundary condition, whereas Fig. 6b–d shows the ground temperature profile when the radiant heat exchange on the surface is taken into account.

3.3. Heat and mass transfer processes in EAHE

Soil temperatures more than 2 m below the surface are close to the annual mean temperature, while the inlet air is the warmest of the year in summer. As air passes through an EAHE, the convective heat transfer takes place between the air and duct surfaces. The enthalpy and the dry bulb temperature of the air decrease along the flow direction. If the duct is long enough and the duct surfaces are cooler than the dew point temperature, condensation may take place. In Fig. 7, heat and moisture balance are represented on a longitudinal control volume in the pipe.

3.4. Heat transfer equations

Differential Eq. (5) describes the heat balance of flowing air when latent heat generation is taken into account:

$$\frac{\partial T_a}{\partial x} + (T_a - T_{w,i})\frac{h_a 2\pi r_0}{m_a c_a} - \frac{g_v l 2\pi r_{p,i}}{m_a c_a} = 0 \tag{5}$$

Differential Eq. (6) describes the heat conduction around the pipe:

$$\rho c_p \frac{\partial T}{\partial t} = \left(\frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{6}$$

where ρc_p and λ are the density, specific heat and the thermal conductivity of the ground. The heat balance for pipe is:

$$(T_a - T_{w,i}) \times h_a \times 2\pi \times r_{p,i} = \frac{(T_{w,i} - T_{w,o})}{(1/2\pi\lambda_p) \times \ln(r_{p,o}/r_{p,i})} \tag{7}$$

Moisture transfer: Differential Eq. (8) describes the moisture balance on the longitudinal element

$$\frac{\partial \rho_v}{\partial x} + (\rho_v - \rho_{v,\mathrm{sat}}(T_{w,i})) \times \frac{\beta_b 2\pi r_{p,i}}{V_a} = 0 \tag{8}$$

4. Algorithms for heat transfer in EAHE

Several theoretical and experimental studies have been made to evaluate the thermal performance of EAHE. Tzaferis et al. [28] studied heat transfer in EAHE with eight algorithms, which can be divided into two groups: the first calculates convective heat transfer from the circulating air to the pipe and then the conductive heat transfer from the pipe to the ground and inside the ground mass; and the second calculate only the convective heat transfer from the circulating air to the pipe. Tzaferis et al. [28] concluded that almost all the proposed algorithms are sufficiently

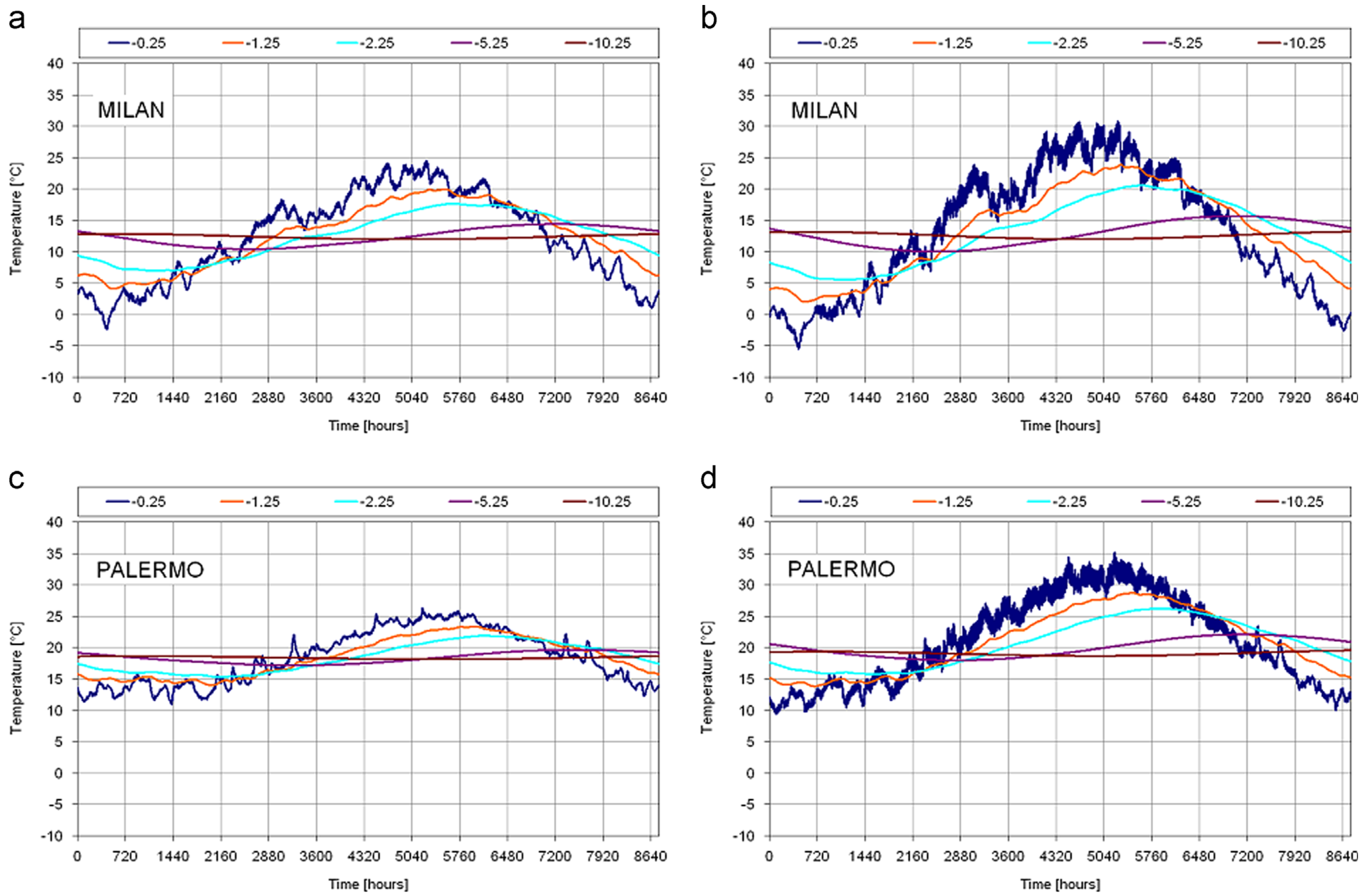

Fig. 6. Effect of the short- and long-wave radiant exchange on ground temperature at different depths: (a) and (c) only external air temperature as a boundary condition, (b) and (d) with radiant heat exchange.

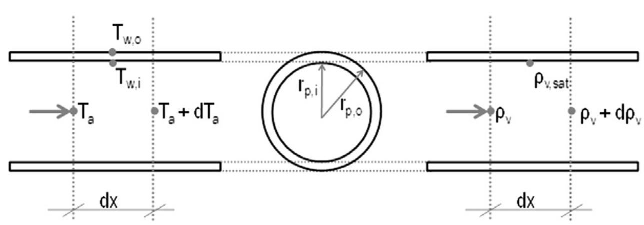

Fig. 7. Heat balance (a) and moisture balance (b) on a longitudinal control volume.

accurate when predicting the temperature of the outgoing air from the EAHE.

4.1. EAHE models to predict the performance

Many models are today available for evaluating the performance of EAHE. They can be divided into:

– analytical methods
– numerical methods.

Thermal performance (temperature performance and energy efficiency) of EAHE can be calculated using a range of approaches [20]:

– specific energy supply [kW h/(m^2y) and W/m^2];
– heat transfer NTU and h_{mean};
– temperature behavior Θ;
– energy efficiency (COP).

Input parameters for the model can be divided into inflexible and flexible [15], as illustrated in Table 2.

Different parametric and numerical models for EAHE have been published in the last 20 years and a wealth of literature has focused on EAHE performance. The heat transfer models for EAHE considered in this paper are summarized in Table 3 in chronological order.

The model developed by Mihalakakou et al. [29] considers that the energy transfer inside the soil is driven by simultaneous heat and moisture transfer gradients along both axial and radial directions. By superimposing the heat transfer from more than one duct, Mihalakakou et al. [30] modified the previous model so that it could simulate multiple-pipe EAHE. The authors defined the difference between the inlet and outlet air temperatures as the EAHE energy potential.

Sodha et al. [31] proposed an analytical model to determine the annual heating and cooling potential of underground air pipe systems. The model assumes that the thermal properties of the soil are constant and homogeneous and ignores condensation and evaporation within the pipes. The model considers the influence that the pipes have on each other and neglects the hourly variations of the time-dependent input parameters (ambient air temperature, solar radiation, relative humidity).

Bojic et al. [32] developed a method to solve heat transfer in the soil by horizontally dividing the earth into a number of parallel layers, each with a uniform temperature. Heat transfer between the soil layers is solved with energy balance equations for each soil layer. Two years later, Bojic et al. [18] modified the method by dividing the earth layers into smaller control volumes.

A numerical model for multiple-pipe EAHE was developed and validated by Hollmuller and Lachal [33]. The model considers complex geometries/designs, more ground characteristics and more boundary conditions. It uses the finite elements method

Table 2
Input parameters for the model according to VDI 4640—Part 4.

Prespecified (inflexible) parameters	Freely selectable (flexible) parameters
Location/weather	Flow rate
Thermal proprieties of the ground: (ρ_E [kg/m^3], λ_E, [W/(m K)], c_E [k J/(kg K)])	Pipe length
Backfilling material	Pipe diameter
Ground water content	Pipe material
Ground stratification	Installation depth
Usable ground area	Distance between grid pipes or from nearby buildings or under
Ground water temperature and level Building cooling load	Control modes

Table 3
Heat transfer models for EAHE.

Authors and method	Objective	Input	Output
Mihalakakou et al. [29]. Transient, implicit numerical model for single pipes	Predict air and soil temperature fields beneath a building	Soil characteristics, geometries, pipe air temperature, and mean annual soil temperature	Undisturbed soil temperature; soil moisture content and circulating-air humidity
Mihalakakou et al. [30]. Numerical model (for multi parallel pipes)	Describe the simultaneous heat and mass transfer inside the pipe and in the soil. The soil′ s natural thermal stratification is taken into account	Independent variables: pipe radius, distance from pipe inlet, and time. Dependent variables: soil temperature and moisture content	Air temperature at pipe outlet
Sodha [37]. Analytical models	Determine the annual heating and cooling potential of underground parallel air pipe systems	Environmental parameters: ambient temperature, relative humidity, and earth/soil temperature. Pipe characteristics	Heating and cooling potential [kW h]
Bojic [18]. Numerical model for two-pipe systems: time-marching method	Calculate energy transfer from soil to EAHE	Soil and pipe characteristics, geometries, solicitation of the soil, pipe air temperature	Heat flux through volume elements, temperature in the volume elements
Hollmuller and Lachal [33]. Explicit numerical model for multi-pipe systems	Predict latent and sensible heat exchanges	Soil properties, shapes, solicitation of the soil, pipe air temperature, surface soil and pipe temperature, and humidity ratio	Latent and sensible energy exchanges (from air to soil) in kW h
Ghosal [34]. Simplified analytical model for greenhouses (solved with MATLAB)	Evaluate EAHE performance in terms of thermal load leveling (TLL) and COP	House design and features, solar radiation, convective heat transfer coefficient from underground earth′s surface to flowing air inside the buried pipes	Temperature of greenhouse air combined with earth-to-air heat exchanger
GHE model [17]. Numerical transient bi-dimensional approach	Calculate energy provided by heat exchanger during cold or warm season	Temperature distribution in soil, incident solar radiation on a horizontal surface, weather data	Yearly energy provided by the ground heat exchanger [kW h/year]
Thiers model [35]. Modal analysis for the resolution of differential equations	Calculate outlet air temperature during simulation period	EAHE shape, outdoor air temperature, soil thermal model: soil characteristics and ambient parameters	Soil temperature as a function of pipe depth, time and distance from the point considered to the left of the foundation slab
Convolutive response factors method [36]. Numerical model	Solve problem of conduction by reducing computational time	Soil properties, composition, annual and daily solicitation of soil, inlet air temperature, surface temperature of soil and pipe	Incoming heat flux is the response factor, steady-state conductance of the system
AGHX model [38]. Quasi 3D finite elements method	Analyze energy performance, which depends on a wide range of parameters	Soil type, pipe and system characteristics, fan efficiency, weather data	Heating and cooling potential

for the resolution. It can also consider water infiltration, pressure losses and the control of air flow direction in the pipes.

Ghosal et al. [34] developed a thermal model to investigate the performance of EAHE connected to a greenhouse. The model is based on the following assumptions: the analysis is based on quasi-steady state conditions, air flow is uniform along the length of the buried pipes and there is no radiative heat exchange between the sides of the buried pipe.

Badescu [17] developed a ground heat exchanger model based on a numerical transient bidimensional approach. He proposed segmentation into sections that are perpendicular to the pipes. In each section, the heat equation is solved with the volume control formulation method. The interaction between different sections is made with the energy balance of the pipe (no lateral heat transfer on the ground is considered).

Thiers and Peuportier [35] consider the interaction between several parallel pipes laid at the same depth. This system uses a finite volume formulation with a limited number of meshes and enables quick calculations. Two concentric cylindrical meshes are used for each pipe. If the pipes are fairly well-spaced, another cylindrical mesh is added; if they are close, the third mesh includes every pipe, so as to take their interactions into account.

One year later Tittelein et al. [36] developed a new numerical model for EAHE; heat flux entering the pipe is expressed as a function of the temperature of the air flowing through the pipe and the external solicitations. A heat balance is then applied for each layer to find the outlet air temperature.

The accuracy of parametric and numerical models can be tested against experimental data for the thermal performance (energy and temperature) of EAHE. The problem with most of the aforementioned models is that it may take a long time to calculate exchanger behavior accurately due to the type of mesh required. However, simulation software can be used to reduce time and simplify EAHE analysis. Several mathematical models for EAHE

Table 4
Software for EAHE models.

	Description	Features	References
EnergyPlus	Simulation software currently supported by the United States Department of Energy. It implements the complete Heat Balance approach	The model developed heat transfer and soil temperature algorithms into a program that simulates EAHE	[39,40]
TRNSYS+Calculation of soil temperature	TRNSYS is a complete and modular simulation environment for the study of dynamic systems	Numerical model that predicts thermal performance of EAHE	[29,41,42,43]
WKM	Design tool developed by Huber Energietechnik AG (Zurich). Commercial software	Output: temperature trend (inlet/outlet), EAHE operating time, heat recovery, winter and summer energy performance	[44,45]
GAEA (Graphische Auslegung von ErdwarmeAustauschern)	Design tools developed by University of Siegen. Commercial software	Output: temperature trend (inlet/outlet), EAHE operating time, winter and summer energy performance, payback time	[46]
L-EwtSim	Design tool developed by DLR Koln (AG-Solar). Downloadable freeware	Output: Temperature profile in tube/pipe, temperature trend, energy performance	[47]
REHAU – Awadukt Thermo Software GHE – 1.03	Design tool developed by REHAU (private tool) for its own in-house use only	Input: Ground and outdoor parameters; air conditioning plan. Output: temperature trend (inlet/outlet), operating time, heat recovery, winter and summer energy performance	–

have been used in simulation software either dedicated to EAHE or to overall building-system analysis. Table 4 shows the characteristics of the most common software.

The EnergyPlus software contains an earth tube mathematical model developed by Lee and Strand [39,40] and it uses a detailed algorithm to calculate soil temperature variation around a specified earth tube/pipe for every time step of the simulation.

EAHE thermal modeling can be evaluated within the Transient System Simulation Software Program (TRNSYS) environment. Researchers have used this software in different ways: Ahmed et al. [48] used the TRNSED application to simplify simulation. Hollmuller and Lachal [43] developed a user-friendly interface with Type 460 “Air-to-soil heat exchangers”. Al-Ajmi et al. [49] used the TRNSYS-IISIBAT program for EAHE model (Type 264) with the sub-soil model (Type 263).

The Widerstands-Kapazitaten-Modell (WKM-LTe, resistance capacity model) is a calculation model for the simulation of earth-to-air heat exchangers. The model is similar to the heat and electricity models [44]. This software creates a yearly simulation of the ground system with heat recovery and bypass, easily integrates weather data, takes into account collective ducts and funnels, calculates pressure drops in the ground, suggests pipe types and ground characteristics, takes into account the influence of a basement, provides an excel input and output interface, and enables air ventilation way and airflow rates to be selected.

The Division of Building Physics and Solar Energy at the University of Siegen, Germany, has developed a commercial software, GAEA (Graphische Auslegung von Erdwaerme Austauschern) for the design of EAHE [46]. This software is based on the calculations of heat exchange between the soil, buried pipes and air in the system; it also takes into account variations in soil temperature, airflow rate and ambient air temperature. An optimization routine enables a choice from a range of layout variations, which influences heat gains and cost. A validation study of GAEA was published by Heidt and Benkert [50].

L-EwtSim is a German freeware. No literature details research using *L*-EwtSim.

REHAU Software was developed as an in-house design tool. The model calculates heat transfer between adjacent elements in defined time steps. For each time step the software takes into account the air flow rate, soil temperature and other influential parameters, e.g. ground water. The software was validated against simulation results from TRNSYS calculation models and results from test areas. The tool performs calculations based on pipe length or set target temperature extremes.

Computational Fluid Dynamics (CFD) has been well known as a powerful method to study heat and mass transfer for many years. CFD codes are structured around the numerical algorithms used to tackle fluid flow problems. It provides numerical solutions of/for/in partial differential equations governing airflow and heat transfer in discretized form.

FLUENT [51] is one example of CFD software used for EAHE simulation. The thermal model of an EAHE system was simulated considering a 3D transient turbulent flow with heat transfer enabled.

Another CFD software used for EAHE simulations is PHOENICS [52]. This method′s solutions imply that the integral conservation of quantities, such as energy, mass and momentum, are exact over any group of control volumes and over the whole calculation domain. The CFD approach, however, requires a great deal of computational resources and lengthy calculation times over a long period.

EAHE are governed by a number of standards and guidelines. European standard EN 15241 [53] proposes a simplified method for calculating ground-to-air heat flux. Part 4 of the German guidelines VDI 4640 [15] (now under review) provides a system description, environmental aspects and air-hygiene recommendations. VDI 4640 also provides an extensive description of the design procedure and distinguishes between small systems for residential buildings with flow rates up to 1000 m^3/h and large systems for higher flow rates. Piping materials have to meet a range of air-duct hygiene and corrosion requirements.

5. HVAC system coupling and building application

In recent years, mechanically ventilated buildings have seen their energy efficiency increase. Hybrid ventilation, which uses mechanical and natural airflow driving forces (alternating or simultaneous), has been used in many building designs [54]. It is based on reducing pressure drop in the ductwork by increasing its cross-sectional area so that natural airflow driving forces, such as buoyancy and wind, can be used to reduce fan energy consumption. When EAHE are incorporated into a hybrid ventilation system, the cross-sectional areas of the duct should be much larger than those of the conventional ducts used in mechanical ventilation systems. Combined EAHE and hybrid ventilation is regarded as a new approach to improving building energy efficiency (Fig. 8).

Fink et al. [55] describe three types of HVAC integration for offices and administration buildings. The first, defined “comfort cooling” (see Fig. 6(a)), is designed to improve comfort. The second, defined “space cooling” is designed to control room temperature (see Fig. 6(b)) in order to avoid exceeding a default

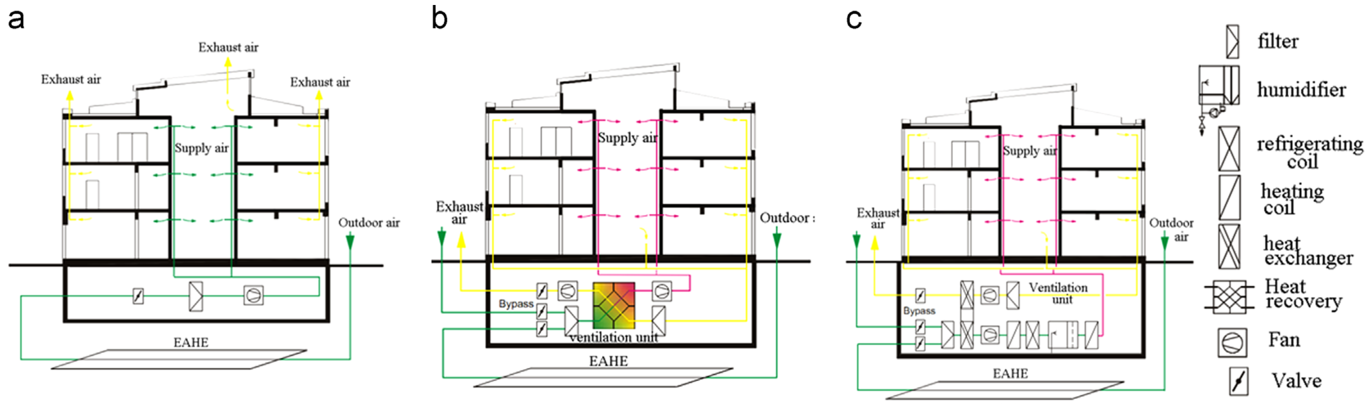

Fig. 8. HVAC system integration: EAHE and ventilation unit [54].

temperature. The last type, defined "support cooling" uses an EAHE to support a conventional cooling system (see Fig. 6(c)).

Boijc [56] studied four devices employing refuse and renewable energy: an air-to-air heat pump (HP), a heat-recovery exchanger (HRE), an air-to-earth heat exchanger (EAHE), and an air-mixing device (MD). A computer was used to study different combinations in order to find one that would consume the least energy. Boijc concluded that the MD and HRE have a major influence on energy savings but that EAHE have a relatively slight influence.

For residential buildings, VDI 4640 recommends that ventilation systems include an efficient heat recovery unit.

Chlela et al. [57] analyzed an EAHE coupled with heat recovery balanced ventilation systems in order to evaluate their impact on the energy consumption and thermal comfort of a detached house. The authors concluded that a balanced ventilation system significantly reduces a building's heat demand and thus its CO_2 emissions. However, the earth-to-air heat exchanger makes a marginal contribution to the energy savings and reducing CO_2 emissions. One advantage during the cold season is that the heat recovery unit is protected against freezing. An EAHE has great potential for improving thermal comfort in summer, but to ensure good thermal comfort throughout the summer, it should be combined with other solutions.

5.1. Building application

An EAHE system is suitable for different types of buildings; Table 5 provides a summary and analysis. The first column contains the building and climate type, as per Kšppen's climate classification: Tropical/megathermal climates, Dry (arid and semiarid) climates, Temperate/mesothermal climates, Continental/microthermal climate, Polar climates, and Alpine climates.

6. Discussion

6.1. EAHE performance and design: Considerations

In order to summarize advice and suggestions for EAHE design, we have included the following aspects that influence overall system performance:

(1) Ground temperature is governed by the aboveground environment. The earth's surface may be blackened or glazed to increase the subsurface temperature, but to decrease the subsurface temperature, the earth's surface can be shaded, painted white or wetted with sprayed water.
(2) Pipe depth and positioning: pipes can be positioned beneath the building or in the ground outside the building foundation. An increase in soil depth above the pipes provides a considerable increase in the system's potential heating capacity [71]. According to Badescu [17], burying the pipe 2 m below the surface is a good compromise between a small yearly temperature excursion (which decreases with depth) and excavation costs (which increase with depth). Ascione et al. [62], however, state that 3 m is an optimum compromise. We may therefore conclude that optimum depth must be evaluated in each case, taking into account that the pipe depth affects the whole system efficiency, as also reported by Esen et al. [13].
(3) Pipe length: an increase in the buried pipe's length causes outlet air temperature to rise, which means that the system's potential heating capacity may also increase [71]. However, there are no signifcant advantages in using pipes over 70 m long [40]. Optimal length depends on climate conditions [62].
(4) Soil cover: Mihalakakou [71] states that bare soil surface may increase a system's heating capacity. Badescu [17] combined his analysis with a cooling mode simulation, concluding that the heat stored by the ground is higher in vegetation-covered soils for heating but is lower for cooling (in absolute values)
(5) Climate and soil composition: the high water content of some soil typologies improves EAHE performance. Soil must be closely packed around the pipe to foster heat exchange, consequently compacted clay or sand is recommended [62].
(6) Pipe radius: an increase in the buried pipe's radius leads to a reduction in the convective heat transfer coefficient; this leads to a lower air temperature at the pipe outlet and thus reduces the system's heating capacity. Moreover, reduced outlet air temperature is associated with increased pipe surface, as the pipe radius increases [71]. Typical diameters are 10 cm to 30 cm but may be as large as 1 m for commercial buildings.
(7) Pipe material: pipe material has little influence on summer and winter performance [17]. The different thermal conductivity values scarcely influence heat exchange, if pipes are the correct depth and length. Concrete pipes require an additional internal coating to prevent radon infiltrations; furthermore the pipe interior must be perfectly hygienic, consequently an antimicrobial coating is recommended [62].
(8) Pipe spacing: if parallel pipe systems are used, pipes should be kept approximately 1 m from each other in order to minimize thermal interaction. Greater spacing was not found to bring any extra benefit [66].
(9) Pipe number: it depends on air-flow requirements, pipe length and layout.
(10) Air velocity: increased air velocity in the pipe leads to a slight decrease in outlet air temperature. This is mainly due to the increase in mass flow. High air velocities are not energy efficient [62].

Table 5
Buildings and projects.

Building type and climate	Method	References
Greenhouse (Greek: Mediterranean climate)	Parametric analysis (TRNSYS)	[20]
Greenhouse (India: humid subtropical climate)	Data measurements and interpretation+analysis with MATLAB	[34]
	Data measurements and interpretation+thermal model developed by Ghoshal and Tiwari	[58]
Farmhouses (India: humid subtropical climate)	Data measurements and interpretation	[59]
Livestock building (Switzerland: oceanic climate)	Data measurements and interpretation+non-steady-state heat flow model	[60]
Multifamily and commercial building (Comparison between Central Europe: oceanic climate, and Southern Europe: Mediterranean climate)	Data measurements and interpretation+dynamic simulation (TRNSYS)	[33]
Commercial buildings: three offices (Germany: oceanic climate)	Data measurements and interpretation+parametric model (NTU method)	[61]
Commercial building: office (Comparison between north Italy: humid subtropical climate, and south Italy: Mediterranean climate)	Dynamic simulation in a range of Italian climates	[62]
Commercial building: office (Belgium: oceanic climate)	Data measurements and interpretation+dynamic simulation (TRNSYS and COMIS)	[63]
Commercial building: office (Germany: oceanic climate)	Data measurements and interpretation+dynamic simulation (TRNSYS)	[64]
	Energy monitoring	[65]
Commercial buildings: offices and administration buildings (reference building—Germany: oceanic climate)	Simulation (WKM and TRNSYS)	[55]
Commercial building: office (Switzerland: oceanic climate)	Data measurements and interpretation	[66]
Residential building (India: humid subtropical climate)	Data measurements and interpretation	[67]
Residential building: three-zones (Comparison between south USA: tropical savannah climate, central USA: humid continental climate, south/west USA: subtropical arid climate, and north USA: semi-arid climate)	Dynamic simulation (EnergyPlus)	[40]
Residential buildings: two-dwelling passive buildings (France: oceanic climate)	Dynamic simulation (COMFIE)	[35]
Residential building: detached house (north Italy: humid subtropical climate)	Data measurements and interpretation	[68]
Residential building: detached house (Kuwait: hot desert climates)	Dynamic simulation (TRNSYS-IISIBAT) in desert climates	[49]
School (Italy: Mediterranean climate)	Simulation with GAEA	[67]
School (Norway: maritime subarctic climate)	Data measurements and interpretation	[69]
School: university (Greek: Mediterranean climate)	Data measurements and interpretation+dynamic simulation (TRNSYS)	[41]
School: laboratory center (China: humid subtropical climate)	Data measurements and interpretation+dynamic simulation (EnergyPlus)	[70]

(11) Seasons: exchanged heat is on average about 1.3 times higher on summer days than on winter days [18].
(12) Control mode: it is closely related to building use. The most convenient solution for office buildings is to use EAHE throughout the day. Thus, a 15-h day is the best solution [62]. The system should be bypassed when the outside temperature enters a certain range (for example 15–22 °C); the system can be controlled by ground temperature or by external air temperature.

7. Conclusions

The European Energy Efficiency Building Directive 2010/31/CE promotes the adoption of passive strategies for buildings in order to achieve high levels of indoor thermal comfort, especially in summer, thus reducing the use of air conditioning systems or avoiding them all together. We looked at EAHE performance and combining EAHE with other passive strategies in order to provide information and suggestions for designing and evaluating EAHE.

EAHE can be installed in different types of climate, such as hot desert, Mediterranean, humid subtropical and oceanic climates. They can be designed both for cool climates such as Western Europe (e.g. Germany, Switzerland) and for warmer countries, such as India and Kuwait.

Many types of buildings combine ventilation systems with EAHE. For residential buildings an optimal combination is greenhouses and EAHE. Moreover, in combination with other low-energy cooling techniques (e.g. night cooling) and good thermal building design, EAHE may eliminate the need for an air-conditioning system in many cases.

Simulation combined with data measurement interpretation is the best way to analyze the real behavior of an EAHE system, but it must be considered alongside building characteristics and building management.

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